Ubiquity: Relativistic Winds from Young Rotation-Powered Pulsars

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Abstract. Recent X-ray observations of young rotation-powered pulsars are providing an unprecedented detailed view of pulsar wind nebulae. For the first time, coherent emission features involving wisps, co-aligned toroidal structures, and axial jets are fully resolved in X-rays on arc-second scales. These structures, which are remarkably coherent and symmetric, are similar to features seen in the optical Crab nebula. In this report, we present the latest high resolution Chandra X-ray images of six young rotation-powered pulsars in supernova remnants. These data suggest an X-ray morphology perhaps common to all young rotation-powered pulsars and serve as a guide for developing the next generation of theoretical models for pulsar wind nebulae.

INTRODUCTION

Young Crab-like pulsars are thought to lose their rotational energy predominantly in the form of a highly relativistic particle wind. Evidence for this wind is manifest as a bright, centrally condensed synchrotron emission nebula, which Weiler & Panagia (1978) referred to as a “plerion”. Models for these pulsar wind nebulae (PWNe) are based on the Crab Nebula, the first known and brightest example. The freely expanding pulsar wind is initially invisible as it travels though the surrounding self-evacuated region. Eventually, the wind encounters the ambient medium where it is reverse-shocked, resulting in the thermalization and re-acceleration of particles. Synchrotron radiation from these particles is most easily observed in the form of a bright radio nebula which acts as a calorimeter of the pulsar’s current energy loss. Models were developed by Pacini and Salvati (1973), Reynolds & Chevalier (1984) and others and subsequently refined (e.g. Kennel & Coroniti 1984; Aron 1998). A review is found in Chevalier (1998).

High resolution Chandra X-ray images of the Crab pulsar show the limitations of the current models. These observations display coherent concentric toroidal structures and jet-like features apparently aligned along the spin axis, and in the direction of the pulsar’s velocity vector. The remarkable structures and alignments clearly delineate the complex magneto-hydrodynamics associated with this pulsar which have yet to be fully explained. Herein we present several more examples of Crab-like pulsars in supernova remnants (SNRs) observed with Chandra, all of which show evidence of similarly orientated toroidal and possible jet-like features. Collectively, these observations suggest, for the first time, the fundamental relationship of these structures to the central engines in young rotation-powered pulsars. We briefly present each pulsar and discuss the implications of their individual and common morphology.

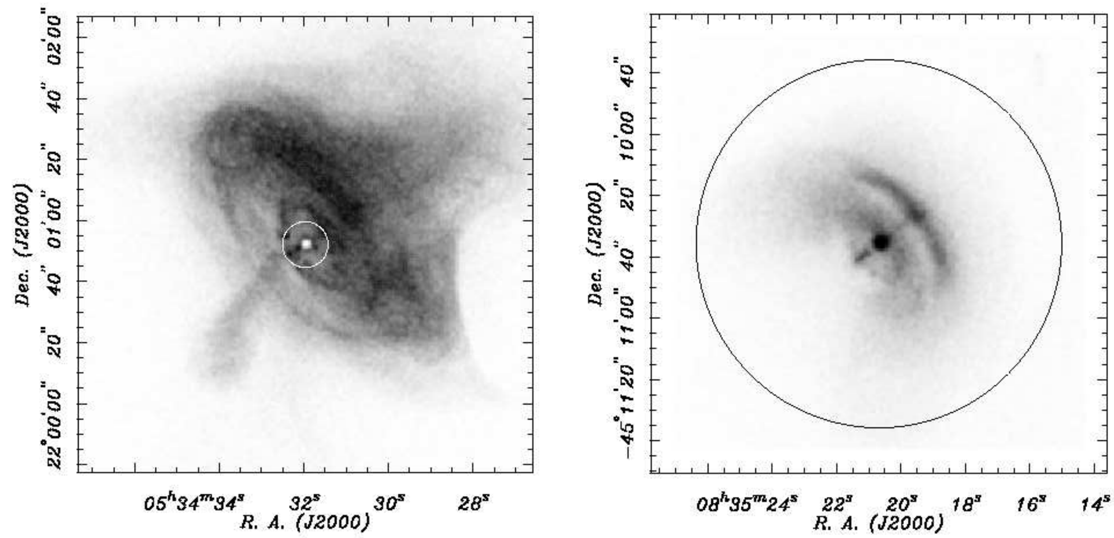

FIGURE 1. A scaled comparison of the relativistic wind nebulae surrounding two young pulsars observed by the Chandra Observatory, (left) the 1,000 yrs Crab pulsar and (right) the 12 kyrs Vela pulsar. These images are displayed with the same plate scale, but the Vela nebula is a factor of 16 times smaller than the Crab assuming distances of 2 kpc (Crab) and 250 pc (Vela); the circles represent the same physical size at the distance of the pulsar. Although Vela is an order of magnitude older and smaller, the two objects are found to be similar in shape and overall brightness distribution. From Helfand, Gotthelf, & Halpern (2001); see also Weisskopf (2000)

NEW CHANDRA OBSERVATIONS

The Chandra Observatory (Weisskopf, O'Dell, and van Speybroeck 1996) has targeted most of the known Crab-like pulsars using one or both of its two imaging focal plane detectors, the High Resolution Camera (HRC) and the CCD-camera (ACIS). Both cameras provide arc-sec imaging over a $\sim 0.5^\circ \times 0.5^\circ$ field-of-view. The HRC allows pulse-phase imaging to isolate the pulsars from their nebulae while ACIS provides moderate resolution spectroscopy. Table I presents a summary of the observational characteristics of the pulsars presented herein. The Chandra images for each of these SNRs are displayed in Fig. 1a-3b.

PSR J0534+2200, The Crab [Fig. 1a] – The remarkable Chandra observation of the Crab nebula has been reported in Weisskopf et. al 2000. As previously mentioned, images from this data set shows toroidal and jet-like X-ray structures aligned along the spin axis. These features were first hinted at by earlier X-ray observation (Aschenbach & Brinkmann 1975) but the quality of the new Chandra images now fully reveals the central engine powering the nebula, clearly delineating its geometry with respect to the optical nebula. The observed morphology displayed in Fig. 1a forms the basis for a comparison with other PWN pulsars. The Crab Nebula, however, is unique amongst young supernova remnants in that it has no discernible SNR shell; the reason for this is not yet satisfactorily explained.

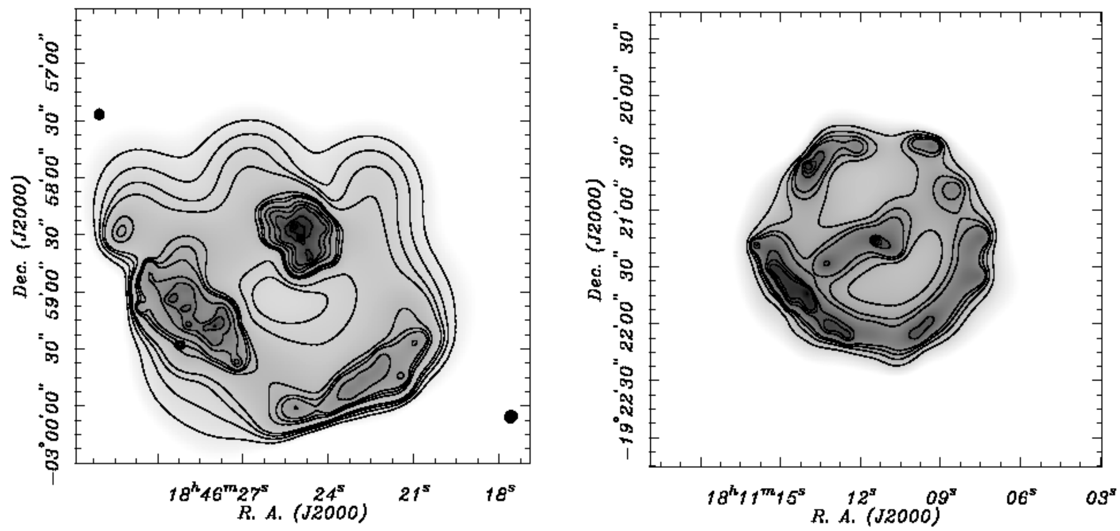

FIGURE 2. Two young supernova remnants observed by the Chandra Observatory containing recently discovered pulsars. (Left) – Kes 75 with its 324 ms pulsar PSR J1846−0258, which has a spin-down age of only 700 yrs. (Right) – G11.2-0.3 contains the 69 ms pulsar PSR J1811−1926, possibly the stellar remnant of the historic supernova of A.D. 386. The resolved pulsars in the center of both images are by far the brightest object in the image which is saturated to highlight the diffuse emission. These images are adaptively smoothed and their respective contour levels and plate scales set the same for comparison. From Helfand & Gotthelf (2001) and Kaspi et al. (2001)

PSR J0835−4510 in Vela XYZ [Fig. 1b] – The 89 ms Vela pulsar was observed twice with the HRC, ~ 3.5 and ~ 35 days following an extreme glitch in its rotation frequency (Helfand, Gotthelf, and Halpern 2001). Most surprisingly was the discovery of a coherent toroidal structure and axial jet remarkably similar to that observed in the Chandra observation of the Crab Nebula. Furthermore, as for the Crab, the axis of symmetry is also along the directions of the pulsar proper motion. Clearly resolved are two concentric arcs which may form tori. The physical size of these structures is 16 times smaller relative to the Crab (see Figure 1), perhaps commensurate with its lesser spin-down energy. Comparison of the two Vela observations shows that the brightness of the outer arc increases significantly while the flux of the pulsar remained relatively steady. If this increase is associated with the glitch, the inferred propagation velocity is $\gtrsim 0.7c$, similar to that seen in the brightening of the optical wisps of the Crab Nebula.

PSR J1846−0258 in Kes 75 [Fig. 2a] – Kes 75 is a young, distant (~ 19 kpc) Galactic shell-type remnant with a central core whose observed properties have long suggested a PWN similar to the Crab Nebula (Becker, Helfand & Szymkowiak 1983). Located within the core of Kes 75 resides the recently discovered PSR J1846−0258 (Gotthelf et al. 2000) – a pulsar with exceptional timing properties: its period, spin-down rate, and spin-down conversion efficiency, are each an order-of-magnitude greater than that of the Crab, most likely as a result of its extreme magnetic field (Helfand & Gotthelf 2001). Although the PWN is found to be noticeable elongated, the statistics of the current observations is insufficient to resolve any detailed Crab-like structure. The association of a shell-type remnant in Kes 75 with a centrally located, coeval pulsar provides strong

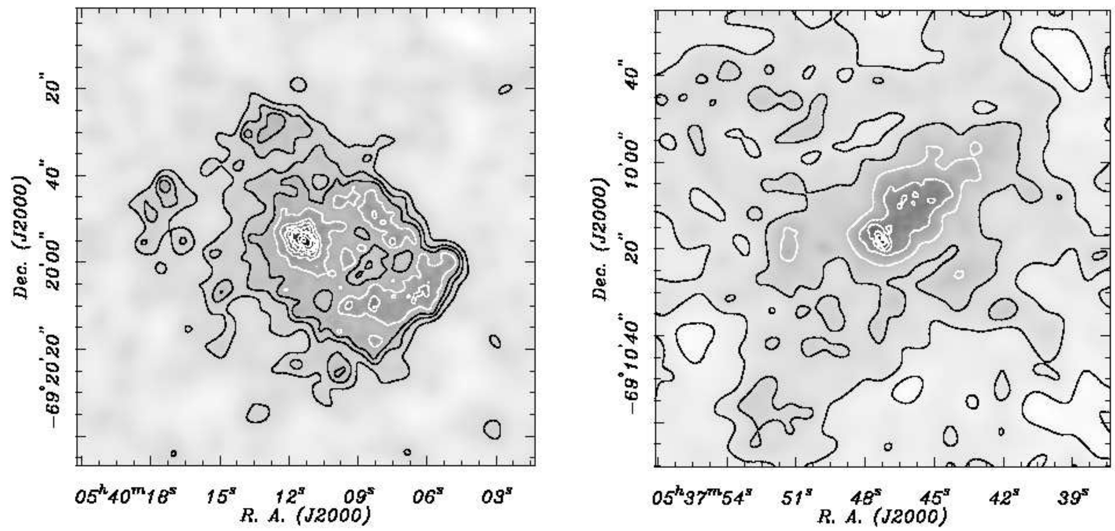

FIGURE 3. A global view around two young Crab-like pulsars located close to each other in the Large Magellenic Clouds. (Left) – the 50 ms pulsar PSR J0540−6919 in SNR 0540-69.3 has an incomplete SNR shell containing an elongated core. Phase resolved blow-up of the core (see Gotthelf & Wang 2000) shows weak evidence of a perpendicular jet. (Right) – the recently discovered 16 ms pulsar PSR J0537−6910 in the N157B nebula, the most rapidly spinning young pulsar known, has faint SNR emission, a bright PWN with an enormous tail of diffuse emission. These images are adaptively smoothed and their respective contour levels and plate scales set the same for comparison. From Gotthelf & Wang (2000) and Wang & Gotthelf (2001).

evidence that neutron stars are born in supernovae explosions. PSR J1846−0258 has the youngest characteristic age ($P/2\dot{P} \sim 700$ yrs) and is likely being spun down rapidly by torques from a large magnetic dipole, just above B_{QED} (see Table 1). The role of the magnetic field is important for understanding the transport and dissipation of particle and magnetic field energy in the relativistic pulsar wind.

PSR J1811−1926 in G11.2−0.3 [Fig. 2b] – The apparently young SNR G11.2−0.3 is a shell-type Galactic remnant containing the 65 ms pulsar PSR J1811−1926 (Torii et al 1998). Based on it location and thermal remnant age estimate, G11.2-0.3 has been proposed as the remnant of supernova SN 386, one of only a few historical supernovae known. The spin-down age of PSR J1811−1926 is, however, 24,000 yrs, a severe discrepancy which suggests the two sources could be unrelated. This is most puzzling, as the pulsar is located near the geometric center of the nearly complete X-ray and radio shell. This suggests the intriguing possibility that the pulsar was born spinning near its current rate or suffered an episode of rapid spin-down. If associated, the symmetry and completeness of the thermal shell strongly constrains the projected magnitude of any initial velocity imparted to the pulsar during its formation.

PSR J0540−6919 in SNR 0540-69.3 [Fig. 3a] – The Chandra calibration observation of the X-ray-bright 50 ms pulsar PSR J0540−6919 in the Large Magellanic Cloud (LMC) has conclusively demonstrated its Crab-like nature (Gotthelf & Wang 2000; Kaaret et al. 2000). Although much older than the Crab (based on its spin-down age), PSR J0540−6919 is contained within a central PWN with toroidal structure similar in

TABLE 1. Young Crab-like Pulsars in Supernova Remnants: Observational Characteristics

Remnant*	Pulsar	Distance (kpc)	P (ms)	$\dot{P}$ $\times 10^{-14}$ (s/s)	Age (kyrs)	$\dot{E}^{\dagger}$ $\times 10^{35}$ (ergs/s)	B_p/B_{QED}**
G11.2−0.3	PSR J1811−1926	5	69	4.4	23.0	63	0.04
Vela XYZ	PSR J0835−4510	0.25	89	12.0	12.0	67	0.08
Kes 75	PSR J1846−0258	19	324	710.0	0.7	82	1.10
SNR 0540-69.3	PSR J0540−6919	LMC	50	48.0	17.0	1516	0.11
Crab Nebula	PSR J0534+2200	2	33	40.0	1.3	4394	0.08
N157B Nebula	PSR J0537−6910	LMC	16	5.1	5.0	4916	0.02

* References for Chandra images – G11.2−0.3: Kaspi et al. (2001); Vela XYZ: Helfand, Gotthelf, & Halpern (2001); Kes 75: Helfand & Gotthelf (2001); SNR 0540-69.3: Wang & Gotthelf (2000), Kaaret et al. (2000); Crab Nebula: Weisskopf et. al (2000); N157B Nebula: Wang, Gotthelf, Chu, & Dickel (2001).

† Ranked by spin-down energy.

** The inferred magnetic field is normalized to the quantum critical field defined as $B_{QED} = m_e^2 c^3/e\hbar = 4.4 \times 10^{13}$ G.

size to that of the Crab. The PWN is just resolved at the distance of the LMC, but analyses of pulse phase-dependent images reveals the characteristic elliptical emission of a Crab-like torus, plus weak evidence for a jet emanating from the pulsar, perpendicular to the major axis of the torus as seen for the Crab and Vela systems.

PSR J0537−6910 in N157B [Fig. 3b] – This remnant is also located in the LMC, only 17 arcmins from SNR 0540-69.3, and contains the recently discovered 16 ms pulsar PSR J0537-6910, the most energetic and rapidly rotating young pulsar known. In addition to the pulsar itself and its surrounding compact PWN, the Chandra X-ray observations resolve a third distinct features, a region of large-scale diffuse emission trailing from the pulsar (Wang, Gotthelf, Chu, & Dickel 2001). This X-ray feature, the largest among all known Crab-like SNRs, is a comet-shaped bubble coexisting with enhanced radio emission and is oriented nearly perpendicular to the major axis of the PWN. It is likely powered by a toroidal pulsar wind of relativistic particles which is partially confined by the ram-pressure from the supersonic motion of the pulsar. Ram-pressure confinement also allows a natural explanation for the observed X-ray luminosity of the compact nebula and for the unusually small X-ray to spin-down luminosity ratio of $\sim 0.2\%$, compared to the Crab pulsar.

DISCUSSION

This preliminary look at the new Chandra images of rotation-powered pulsars hint at what might be learned from these observations. Common to these pulsars is their location in the centers of their respective SNR. Apparently these pulsars have not travelled far from their origin. Collectively, these images provide important constraints on the average birth-kick velocity imparted to young pulsars.

The conjecture that the Crab Nebula is the result of the historic supernova SN 1054 provides a direct link between neutron stars formation and supernovae explosions. The

case may be better made, however, by pulsars residing in identifiable thermal SNR shells, apparently absent for the Crab. The 1000-yr young Crab may be in a pre-shell evolutionary stage; however, a counter example is provided by Kes 75, whose pulsar has a similar spin-down age coeval with its SNR. Furthermore, N157B and G11.2$-$0.3 show only weak shell emission, perhaps like the Crab, but their characteristic ages are much older. As often suggested, the spin-down age is likely unreliable for young pulsars. This notion is furthered advanced by the association of G11.2$-$0.3 with SN 386, which is inconsistent with the spin-down age of PSR J1811$-$1926. The standard assumptions used to associate the spin-down age with the "true" pulsar age may well be violated for young pulsars.

Perhaps ultimately more revealing is the common alignment of the symmetry axis for several of the PWN tori and jets along the direction of the pulsar's velocity vector, when known. Quite inscrutable is the ostensible chance sky alignment of the principle axis for the observed PWNs with position angle of ~ 45 degs. What is clear, however, is that the observed complex toroidal and jet structures are likely ubiquitous to young rotation-powered pulsars. Furthermore, imaging-spectroscopy of these feature are consistent with a highly energetic particle wind emitting non-thermal synchrotron radiation. Of course much theoretical work is needed to model these remarkable structures.

ACKNOWLEDGMENTS

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